PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN H $\rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
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This work is dedicated to the living and loving memory of Jacob Myhre.

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Without so many two- and four-legged blessings along the way, I could never have made it to this point in my academic career. Thus, I begin by giving my endless gratitude to my high energy physics mentors, Professors Andrey Korytov and Guenkah Mitselmakher, for granting me this one-of-a-kind opportunity to do real *science* at CERN.

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Finally, to Existence, for this unpredictable, unbelievable blip of an experience called Life.

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PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN $\mathrm{H} \to 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

Jake Rosenzweig

December 2022

Chair: Andrey Korytov
Co-Chair: Guenakh Mitselmakher
Major: Physics

The mass of the Higgs boson is measured in the $\mathrm{H} \to \mathrm{ZZ}^{*} \to 4\ell$ ($\ell = \mathrm{e}, \mu$) decay channel and is found to be $m_{\mathrm{H}} = 125.38 \pm 0.11\,\mathrm{GeV}$; the most precise measurement of m_{H} in the world to date. The data for the measurement were produced from proton-proton (pp) collisions at the Large Hadron Collider with a center-of-mass energy of 13 TeV during Run 2 (2016–2018), corresponding to an integrated luminosity of $137.1\,\mathrm{fb}^{-1}$, and were collected by the Compact Muon Solenoid experiment. This measurement uses an improved analysis technique in which the final state muon tracks are constrained to originate from the primary pp vertex. Using data sets from the same run, a search for low-mass dilepton resonances in Higgs boson decays to the 4ℓ final state is also conducted. No significant deviation from the Standard Model prediction is observed.

CHAPTER 1
SEARCH FOR LOW-MASS DILEPTON RESONANCES IN THE $\mathrm{H} \rightarrow 4\ell$ CHANNEL

1.1 Motivation

As mentioned in Sec. **??**, even though the Higgs boson has been well studied and *appears* to be consistent with the SM Higgs boson, a single experiment that shows BSM activity (i.e., *any* deviation from SM prediction) is all that is required to defenestrate this idea. For example, it may be the case that the Higgs boson (H) decays into particles other than those found in the SM. This chapter details such an analysis, which follows similar topologies to the one studied in Chapter **??** ($\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow 4\ell$), specifically $\mathrm{H} \rightarrow \mathrm{ZX} \rightarrow 4\ell$ and $\mathrm{H} \rightarrow \mathrm{XX} \rightarrow 4\ell$, where X is a BSM low-mass dilepton resonance.

1.2 Results

An analysis of the m_{Z_2} spectrum is performed to look for any possible low-mass dilepton resonances. In the case of $\mathrm{H} \rightarrow \mathrm{Z_D Z_D}$, in which both of the daughter particles are identical, then a peak in the m_{Z_2} spectrum is expected at $(m_{\mathrm{Z}_1} + m_{\mathrm{Z}_2})/2$.

A simple counting experiment is performed in many bins across the m_{Z_2} spectrum. Using events selected from the $\mathrm{ZZ_D}$ event selection, 353 mass hypotheses m_i are considered for m_{Z_2}. The idea is to scan over the entire m_{Z_2} range (4.20–34.98 GeV) in very fine m_{Z_2} bins, while avoiding the Υ $\mathrm{b\bar{b}}$ bound states. To achieve the desired bin width fineness, each subsequent mass hypothesis is increased by 0.5% of its previous value. Thus, the mass hypotheses are given by:

$$m_i = 4.20 \times 1.005^i \,\mathrm{GeV}, \text{ where } i = 0, 1, 2, \ldots, 129, 202, 203, 204, \ldots, 425.$$

The bin width is chosen to be two times the m_{Z_2} resolution. Concretely, the bin width is equal to 0.04 (0.10)$\times m_i$ for the 4μ and 2e2μ (4e and 2μ2e) final states.

For each m_i, an overall likelihood model ($\mathcal{L}_{m_i}$) is defined as:

$$\mathcal{L}_{m_i} = \mathcal{L}_{m_i}^{\mathrm{SR}} \mathcal{L}_{m_i}^{\mathrm{sb}},$$

where $\mathcal{L}_{m_i}^{\mathrm{SR}}$ is the likelihood that the parameters of interest (θ_k) describe the number of events $\left(n_{m_i,\ell}^{\mathrm{SR}}\right)$ found inside the signal region (SR) for this m_i in a given final state (ℓ), and similarly, $\mathcal{L}_{m_i}^{\mathrm{sb}}$ is the likelihood that the same parameters describe the number of events $\left(n_{m_i,\ell}^{\mathrm{sb}}\right)$ found inside the sidebands (sb)—i.e., outside the SR—for this m_i in a given final state (ℓ).

Both likelihoods for a given m_i are themselves products of Poisson probabilities[1], which are defined as:

$$\mathcal{L}_{m_i}^{\mathrm{SR}} = \prod_{\ell} \mathrm{Po}\left(n_{m_i,\ell}^{\mathrm{SR}} \,\middle|\, \mu n_{s,m_i,\ell}\,\rho_{s,m_i,\ell} + \mu_{\mathrm{H}} n_{\mathrm{H},m_i,\ell} + \sum_{b} n_{b,m_i,\ell}\,\rho_{b,m_i,\ell} \right)$$

and

$$\mathcal{L}_{m_i}^{\mathrm{sb}} = \prod_{\ell} \mathrm{Po}\left(n_{\ell}^{\mathrm{sb}} \,\middle|\, \mu_{\mathrm{H}} n_{\mathrm{H},\ell} + \sum_{b} n_{b,\ell}\,\rho_{b,\ell} \right),$$

where μ is the signal strength parameter,

n_ℓ is the number of

$\mathrm{CL_s}$ [1].

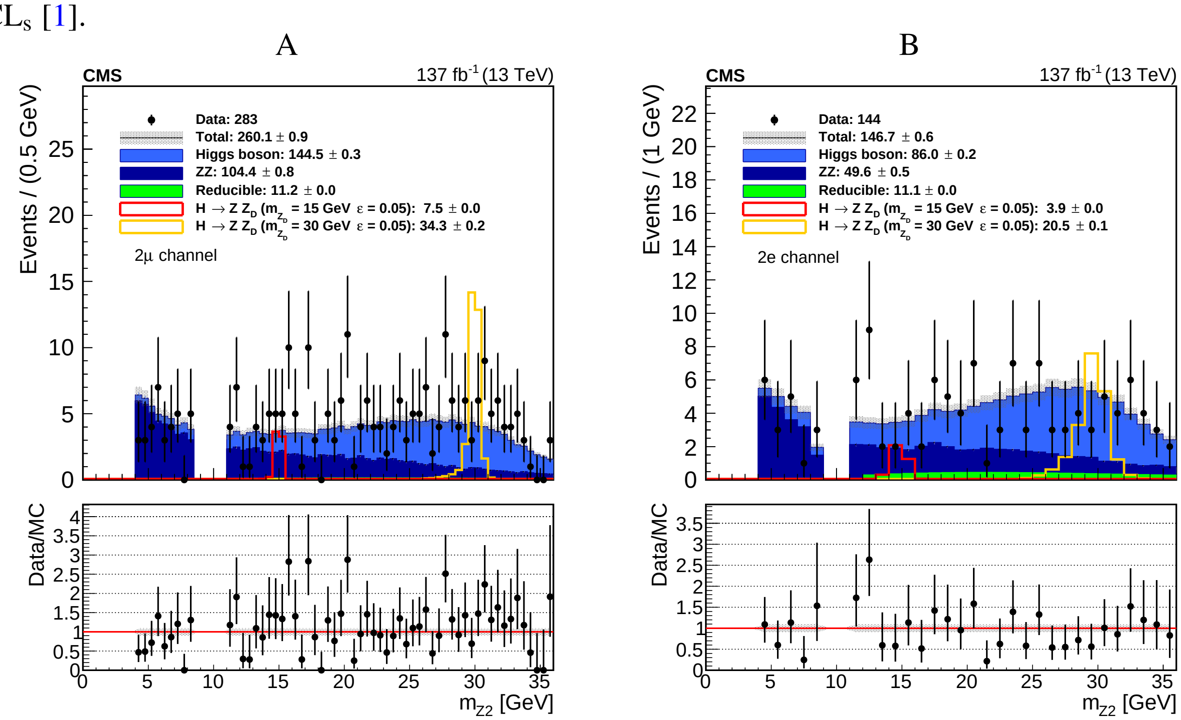
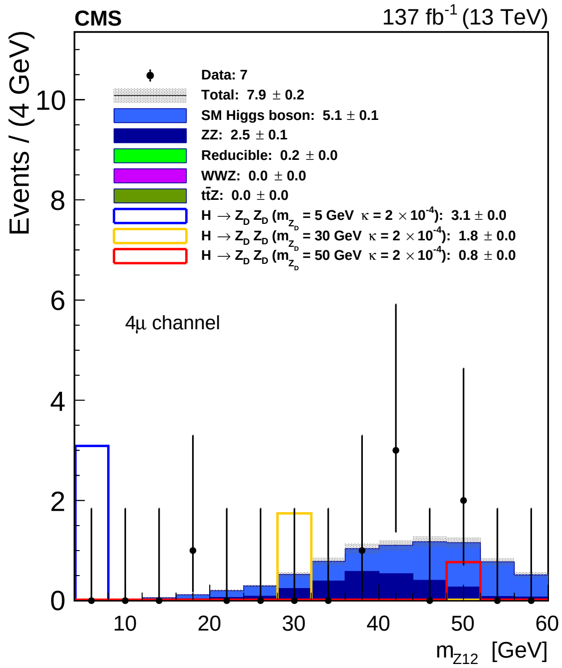


Figure 1-1. testing more

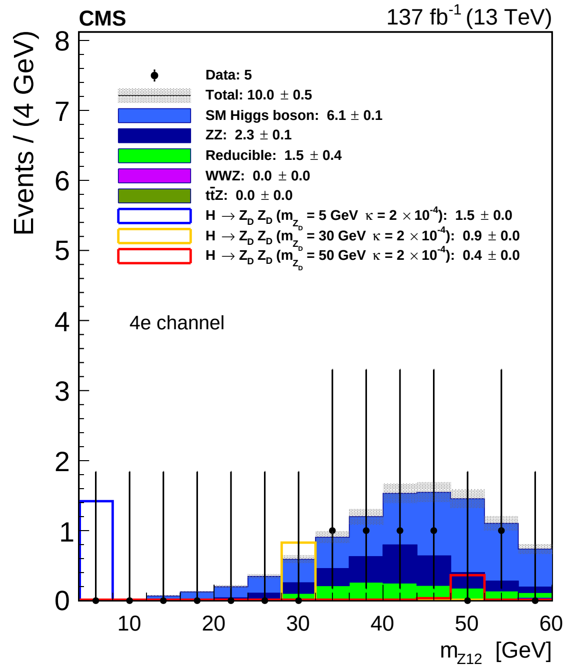
[1] If the number expected events (on average) is λ, then the probability to observe x events is given by the Poisson distribution: $\mathrm{Po}(x \mid \lambda) = \frac{e^{-\lambda}\lambda^x}{x!}$

A



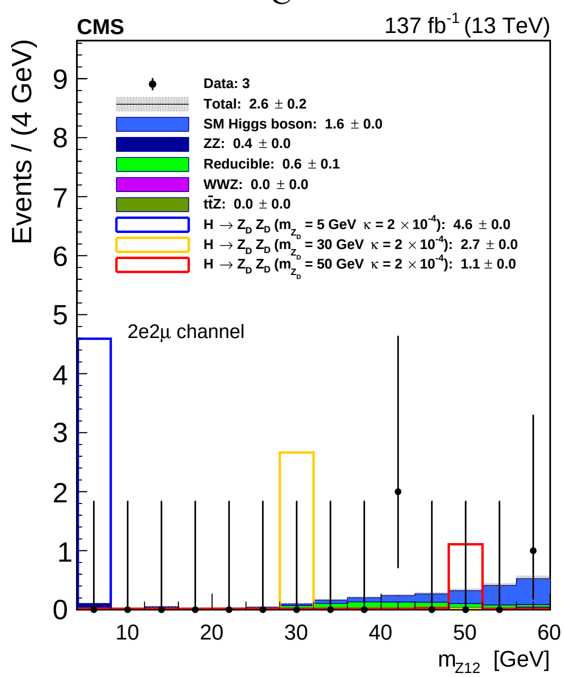
CMS
137 fb-1 (13 TeV)
Data: 7
Total: 7.9 ± 0.2
SM Higgs boson: 5.1 ± 0.1
ZZ: 2.5 ± 0.1
Reducible: 0.2 ± 0.0
WWZ: 0.0 ± 0.0
tt̄Z: 0.0 ± 0.0
H → ZD ZD (mZD = 5 GeV κ = 2 × 10-4): 3.1 ± 0.0
H → ZD ZD (mZD = 30 GeV κ = 2 × 10-4): 1.8 ± 0.0
H → ZD ZD (mZD = 50 GeV κ = 2 × 10-4): 0.8 ± 0.0
4μ channel
Events / (4 GeV)
mZ12 [GeV]

B

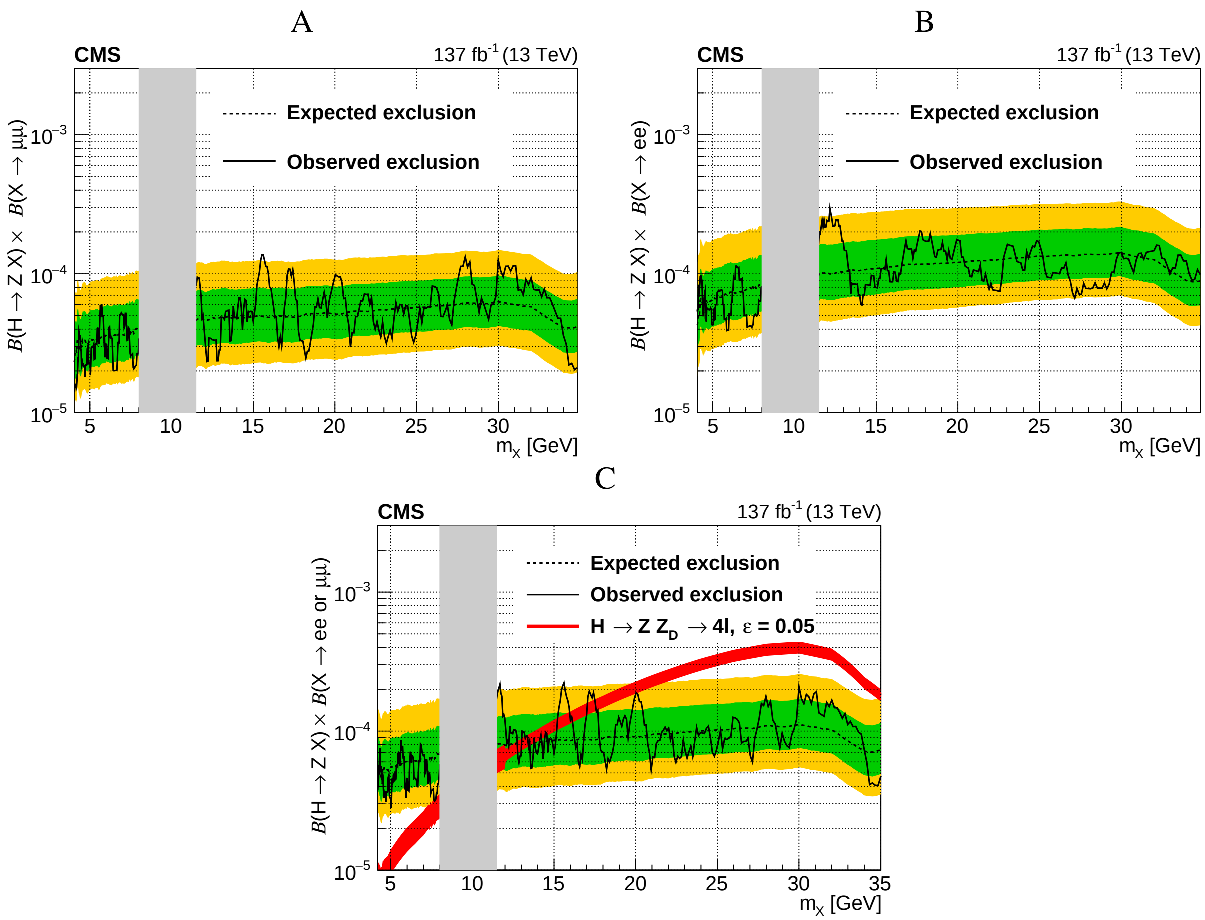


CMS
137 fb-1 (13 TeV)
Data: 5
Total: 10.0 ± 0.5
SM Higgs boson: 6.1 ± 0.1
ZZ: 2.3 ± 0.1
Reducible: 1.5 ± 0.4
WWZ: 0.0 ± 0.0
tt̄Z: 0.0 ± 0.0
H → ZD ZD (mZD = 5 GeV κ = 2 × 10-4): 1.5 ± 0.0
H → ZD ZD (mZD = 30 GeV κ = 2 × 10-4): 0.9 ± 0.0
H → ZD ZD (mZD = 50 GeV κ = 2 × 10-4): 0.4 ± 0.0
4e channel
Events / (4 GeV)
mZ12 [GeV]

C



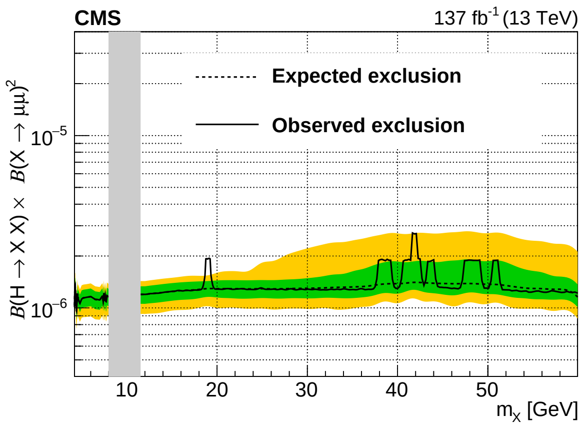
CMS
137 fb-1 (13 TeV)
Data: 3
Total: 2.6 ± 0.2
SM Higgs boson: 1.6 ± 0.0
ZZ: 0.4 ± 0.0
Reducible: 0.6 ± 0.1
WWZ: 0.0 ± 0.0
tt̄Z: 0.0 ± 0.0
H → ZD ZD (mZD = 5 GeV κ = 2 × 10-4): 4.6 ± 0.0
H → ZD ZD (mZD = 30 GeV κ = 2 × 10-4): 2.7 ± 0.0
H → ZD ZD (mZD = 50 GeV κ = 2 × 10-4): 1.1 ± 0.0
2e2μ channel
Events / (4 GeV)
mZ12 [GeV]



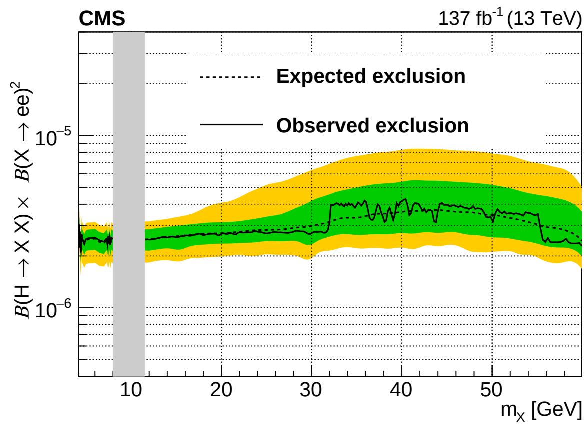
A
CMS
137 fb-1 (13 TeV)
Expected exclusion
Observed exclusion
B(H → Z X) × B(X → μμ)
mX [GeV]
B
CMS
137 fb-1 (13 TeV)
Expected exclusion
Observed exclusion
B(H → Z X) × B(X → ee)
mX [GeV]
C
CMS
137 fb-1 (13 TeV)
Expected exclusion
Observed exclusion
H → Z ZD → 4l, ε = 0.05
B(H → Z X) × B(X → ee or μμ)
mX [GeV]

Figure 1-2

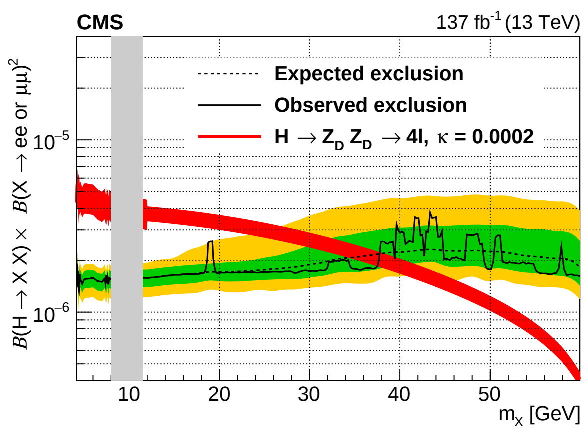
A


CMS
137 fb^{-1} (13 TeV)
Expected exclusion
Observed exclusion
$B(H \to XX) \times B(X \to \mu\mu)^2$
10^{-5}
10^{-6}
10
20
30
40
50
m_X [GeV]

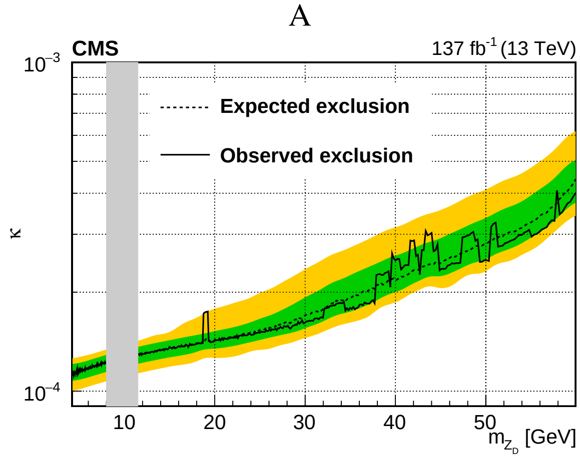
B


CMS
137 fb^{-1} (13 TeV)
Expected exclusion
Observed exclusion
$B(H \to XX) \times B(X \to ee)^2$
10^{-5}
10^{-6}
10
20
30
40
50
m_X [GeV]

C


CMS
137 fb^{-1} (13 TeV)
Expected exclusion
Observed exclusion
$H \to Z_D Z_D \to 4l$, $\kappa = 0.0002$
$B(H \to XX) \times B(X \to ee \text{ or } \mu\mu)^2$
10^{-5}
10^{-6}
10
20
30
40
50
m_X [GeV]

A


CMS
137 fb^{-1} (13 TeV)
Expected exclusion
Observed exclusion
κ
10^{-3}
10^{-4}
10
20
30
40
50
m_{Z_D} [GeV]

REFERENCES

[1] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554.

BIOGRAPHICAL SKETCH

Jake Rosenzweig had the best childhood anyone could ask for, growing up in Jacksonville, FL: enjoying video games with excellent friends, playing football on the beach, and having plenty of opportunity to make mistakes. He graduated from the University of Florida in 2011 with a B.S. in chemistry, while maintaining his sanity by getting minors in education and Latin. He enjoys building things from scrap, weightlifting, hiking in the Coloradoan mountains, gardening, silence, and—most of all—receiving the beleaguered stare from his wife after telling her a *particularly* bad dad joke.